Coal-based Bricks & Blocks (CBBs): Process Development to Prototype Fabrication Coupled with Techno-Economic Analysis and Market Survey

TechConnect
WORLD INNOVATION
Conference & Expo

June 19-21, 2023

Washington, DC

PI: Dr. Randy Vander Wal

Team Members:
James Heim
Schobert Intl. LLC
ADI Analytics
Blaschak Coal Corp.

Funding Acknowledgement:

This material is based on work supported by the Dept. of Energy under Award Number DE-FE0031987.

PennState
College of Earth and Mineral Sciences

John and Willie Leone Family
Department of Energy and Mineral Engineering

Introduction

- Bricks and blocks form the literal cornerstone of our societal infrastructure, since they constitute (at least in part) the primary material in almost all construction projects.

- They are used in a wide range of applications which include, to name just a few, walls, floors and walkways, load-bearing foundations, retaining walls, steps, garden walls and planters, and firepits.

- Ideally, bricks should possess high compressive strength, durability, and little to no water permeability, and should resist thermal expansion and contraction.

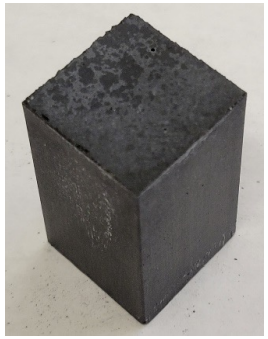
Credit: Parham Taghioff

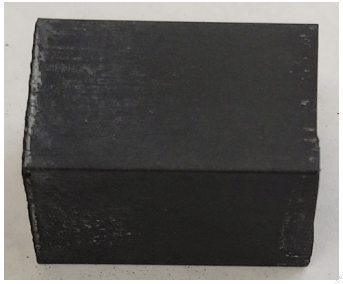
Credit: Peters' Patio & Landscape, Inc.

Overview

- The United States' coal value chain can be extended by manufacturing carbon products directly from coal instead of using derived feedstocks.
- Coal-based construction materials contribute to cleaner energy, cleaner water and cleaner air – which will benefit our society and our economy.
- This project will evaluate the ability of **coal-based bricks and blocks (CBBs)** to compete on price and quality, identifying competitive strengths and limitations.
- Project motivations:
  - To rehabilitate the economy in coal communities
  - To repurpose coal to non-fuel use
  - To promote ease of use with lighter, stronger, interlocking bricks

Anthracite to Bricks



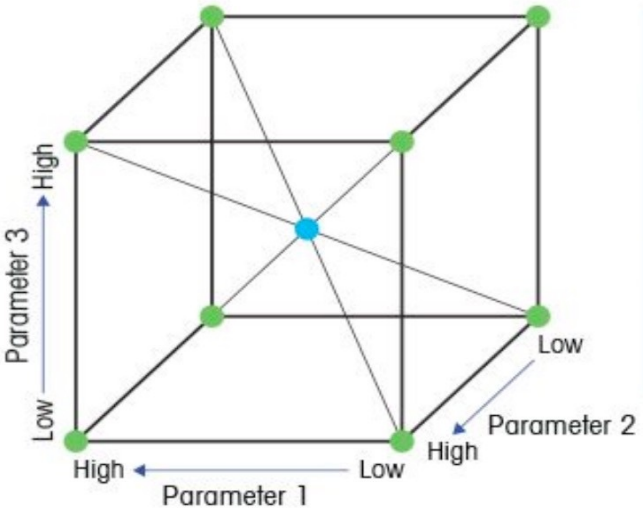


Lab-scale CBBs

PennState College of Earth and Mineral Sciences | John and Willie Leone Family Department of Energy and Mineral Engineering

Approach

Design of Experiments (DoE)



½ Fractional Factorial Design: Design Matrix

2^{3-1} Experiment

X_1	X_2	X_3	X_1X_2	X_1X_3	X_2X_3	$X_1X_2X_3$
−	−	−	+	+	+	−
+	−	−	−	−	+	+
−	+	−	−	+	−	+
+	+	−	+	−	−	−
−	−	+	+	−	−	+
+	−	+	−	+	−	−
−	+	+	−	−	+	−
+	+	+	+	+	+	+

Factors:
- wt.% plastic binder
- proportions of anthracite size fractions,
  e.g., fraction percentages 30/70 versus 70/30
- CB additive amount

Response(s):
Compressive strength, permeability, density, hardness

Identifying optimal composition

Thermoplastic Methods:
- Extrusion
- Injection molding
- Hot-press molding

Thermoplastics tested:
- Virgin/PCR polyethylene, polypropylene, polystyrene
- Virgin polycarbonate, and polyamide 6/6

- **Thermoset method** requires only mixing and molding.
- **Epoxy system** is Epon 862 resin with Epikure 3140 hardener and various modifiers.

PennState College of Earth and Mineral Sciences | John and Willie Leone Family Department of Energy and Mineral Engineering

Economic and Commercialization Assessment

- **Techno-economic Analysis (TEA)**
  - Economic analysis will include estimating the capital and operating costs over equipment service life.
  - TEA analysis will reflect the reduced energy cost for CBBs and reduction in CO2 emissions.

- **Market Survey for CBB and Price Analysis**
  - The survey will benchmark CBB mechanical and material properties relative to commercial brick/block requirements.

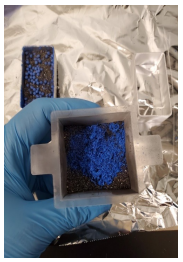
- **Technology Gap Assessment**
  - Identifying required R&D for scaleup and commercialization.

- **Key outcomes** of the TEA will include breakeven prices for CBBs in various market segments and applications.

Thermoplastic CBBs: Hot-Press Molding Process

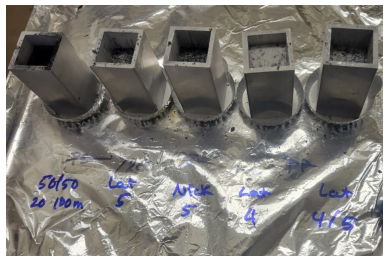
Virgin or post-consumer re-cycled (PCR) plastic binder

Plastic is ground to <850 um



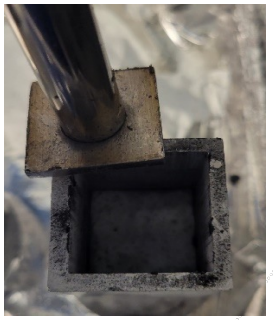
Plastic & anthracite are dry-mixed

Application of mold release

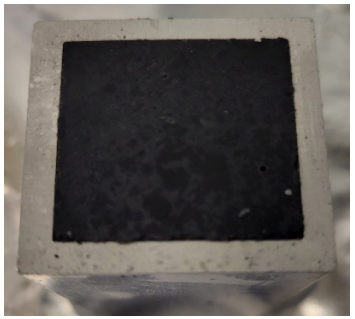


Molds are filled and compacted

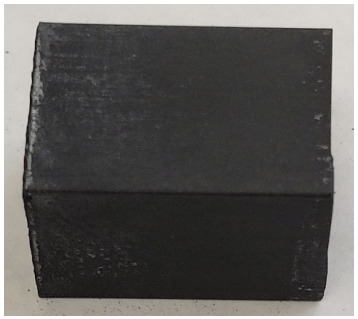
Baked according to melting temperature of the plastic



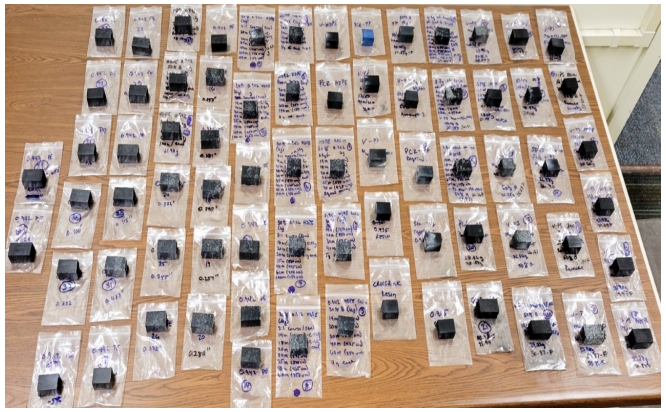
Compaction directly after removal from heat



Cooled at room temperature for 30 min.



Brick is decoupled from mold



CBBs: anthracite particle packing matrix

PennState College of Earth and Mineral Sciences

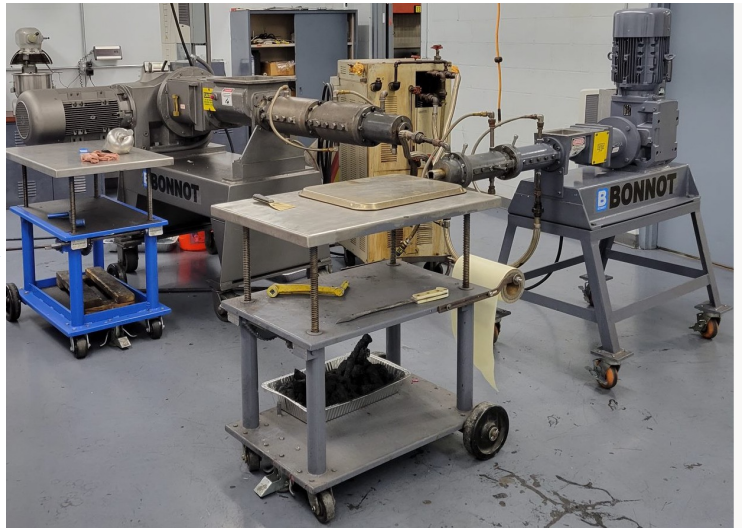
John and Willie Leone Family Department of Energy and Mineral Engineering

Thermoplastic CBBs: Extrusion Process

Anthracite is placed in a pan and covered

Pans are loaded into convection oven to remove moisture

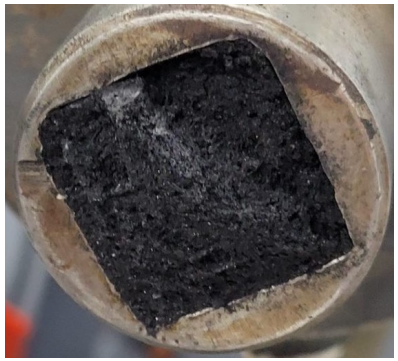
Plastic & anthracite are dry-mixed



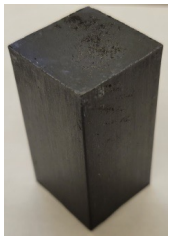
Barrel and nozzle are preheated according to transition temperatures

or

Mixture is loaded into hopper. Left image is PCR thermoplastic and right is virgin thermoplastic.



Homogeneous mixture is extruded, cut, and cooled

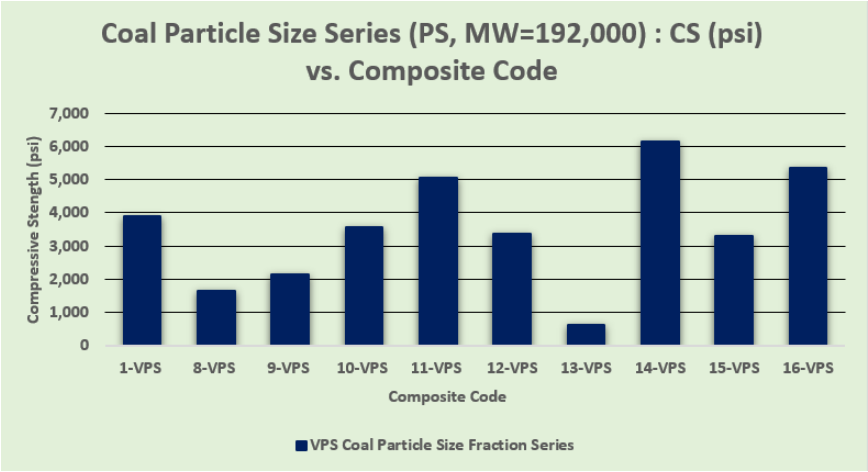


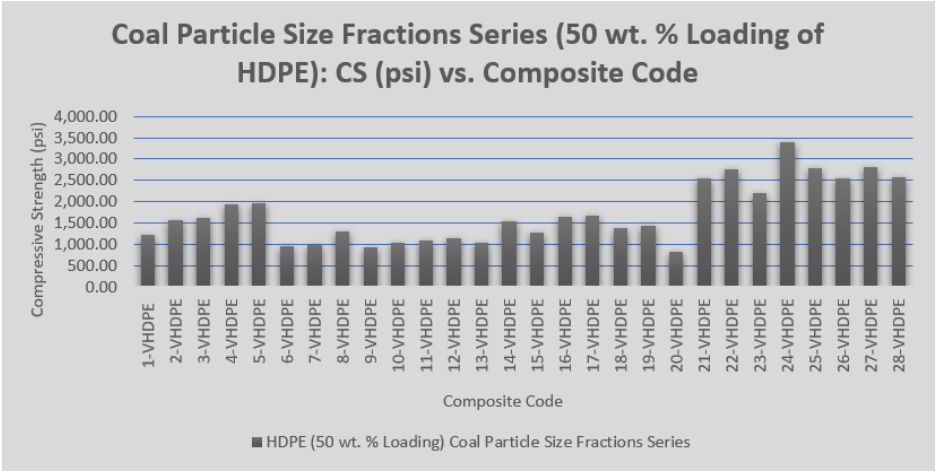
Thermoplastic CBBs

PennState College of Earth and Mineral Sciences

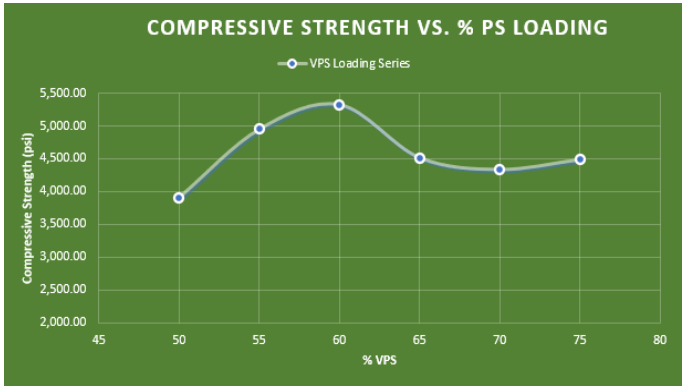
John and Willie Leone Family Department of Energy and Mineral Engineering

Thermoplastic CBBs Compressive Strength Results





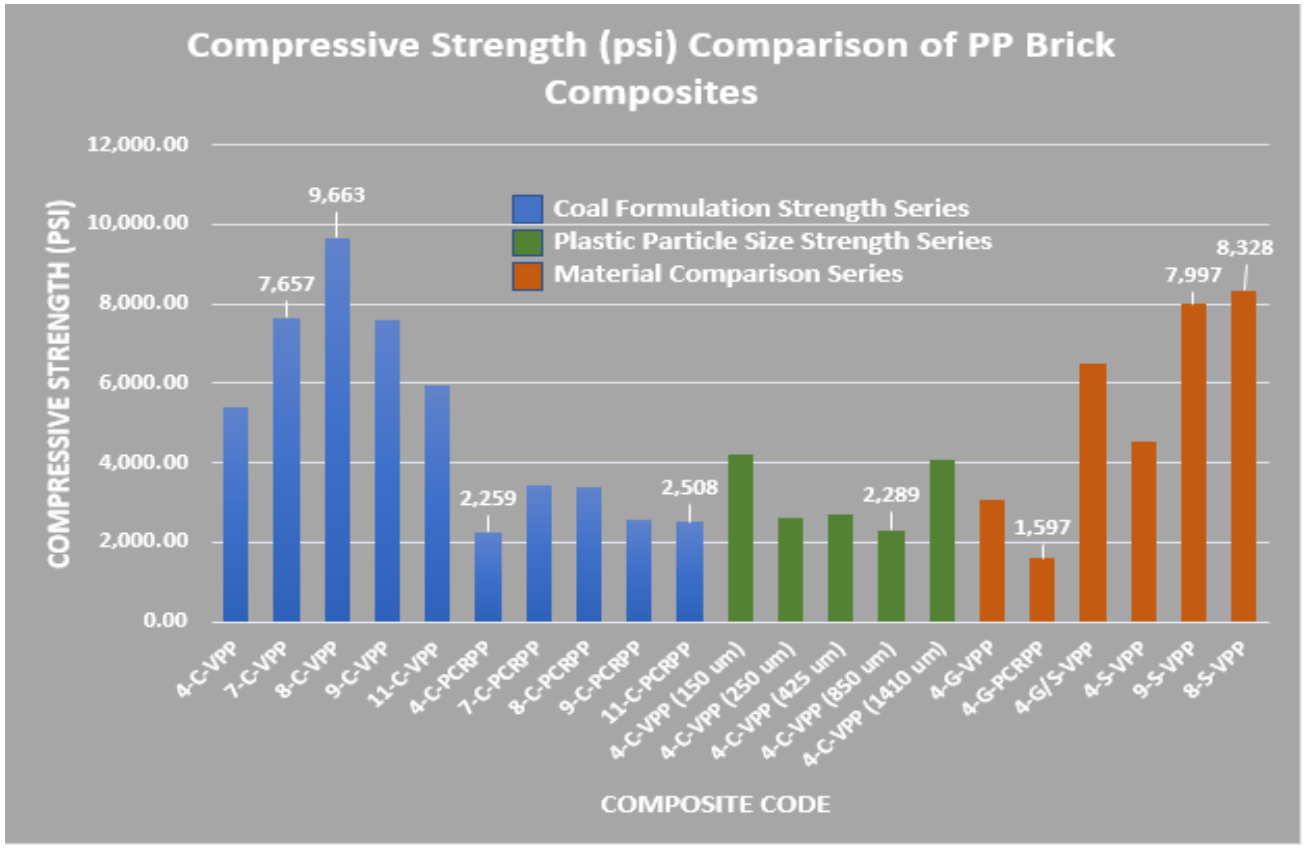
Various compressive strength studies



PennState
College of Earth and Mineral Sciences

John and Willie Leone Family
Department of Energy and Mineral Engineering

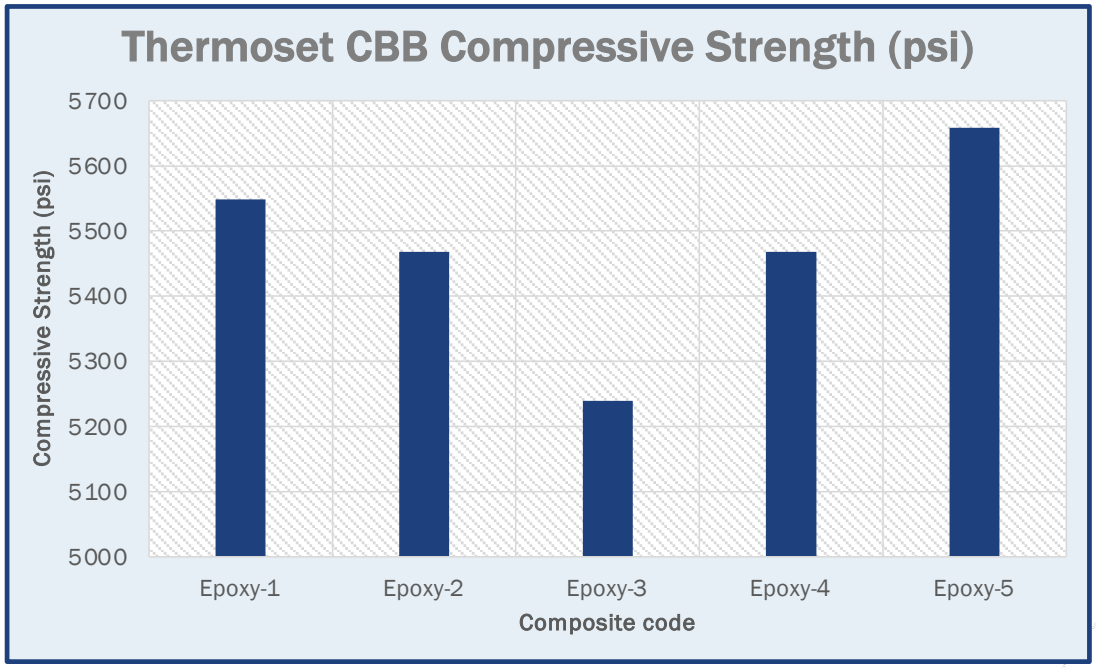
Thermoplastic CBBs Compressive Strength Results



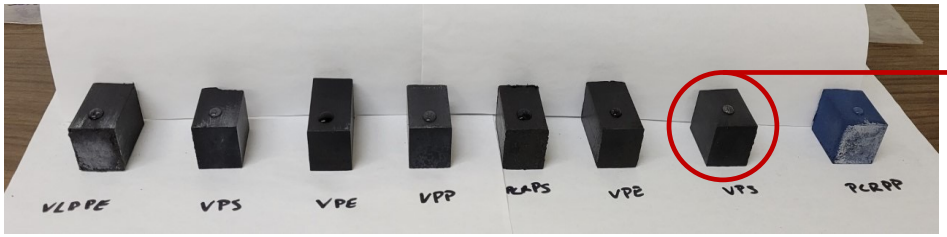
Various compressive strength studies

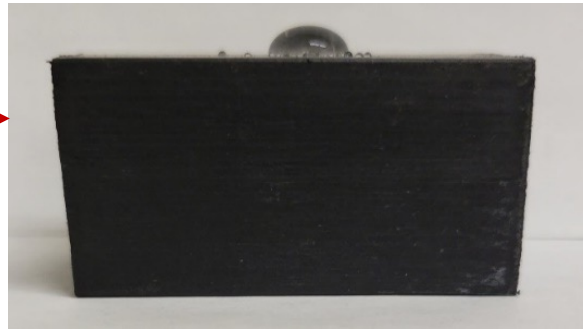
Thermoset CBBs Compressive Strength Results

- Further testing of thermoset bricks needs to be conducted to find their ultimate strength.
- Only one of the five CBB composites fractured before the upper limit of the testing equipment (49.5 KN) was reached.

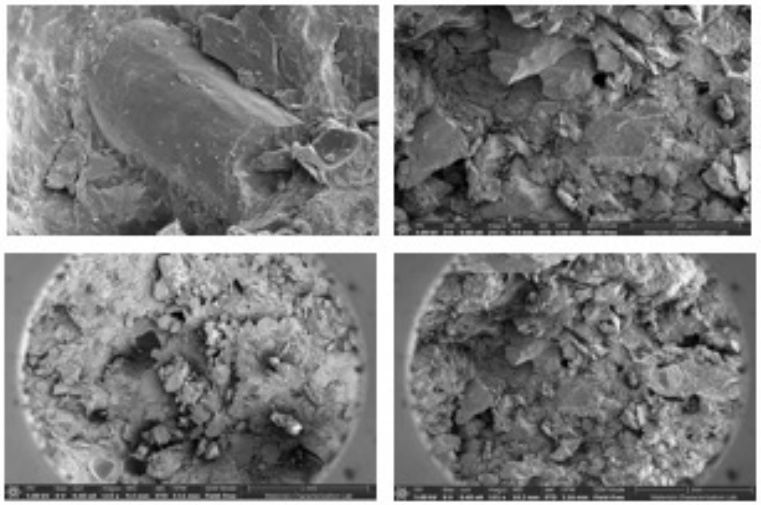


Material characterization (density, porosity, permeability, microscopic structure):





Contact angle showing hydrophobicity of various virgin/PCR thermoplastics and anthracite composites



SEM to investigate surface interactions between coal and thermoplastic particles and dispersion homogeneity

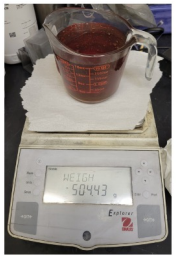
Apparent density calculated by Archimedes Method

PennState College of Earth and Mineral Sciences

John and Willie Leone Family Department of Energy and Mineral Engineering

Progress and Current Status of Project

Thermoset CBB Fabrication Process



Components are weighed

Weighed anthracite, hardener & resin/modifier

Hardener is added to premixed resin/modifier

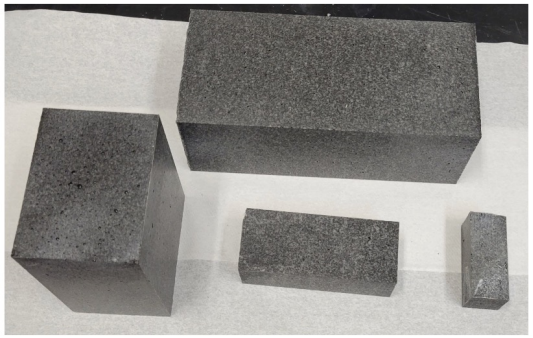
Anthracite is added to epoxy system

CBB mixture

Mixture is poured into molds and vibrated to remove bubbles

Push stamp is used to decoupled CBB after 24 h of curing

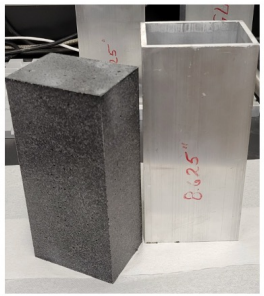
CBBs are cured at 100° C for 1 h

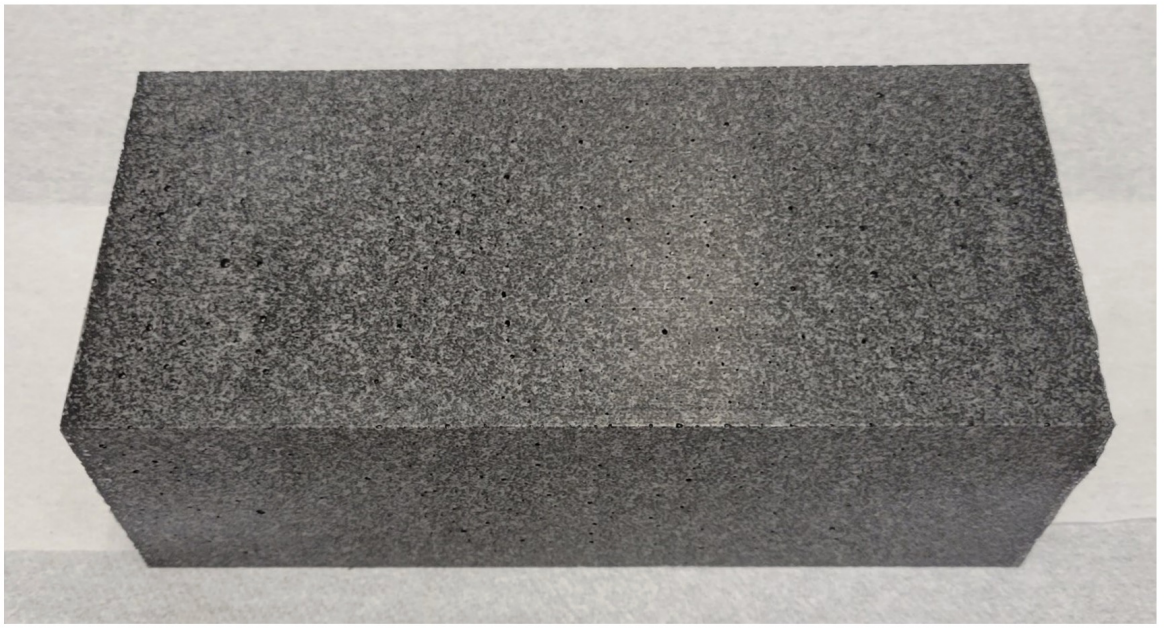


Various CBB sizes awaiting testing

Progress and Current Status of Project

Full-Scale CBB Images

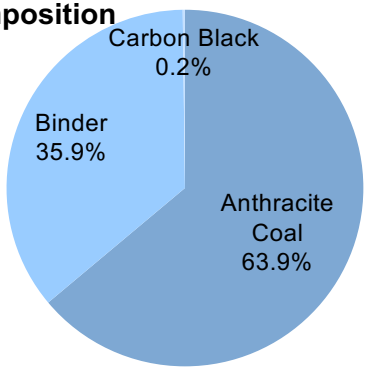




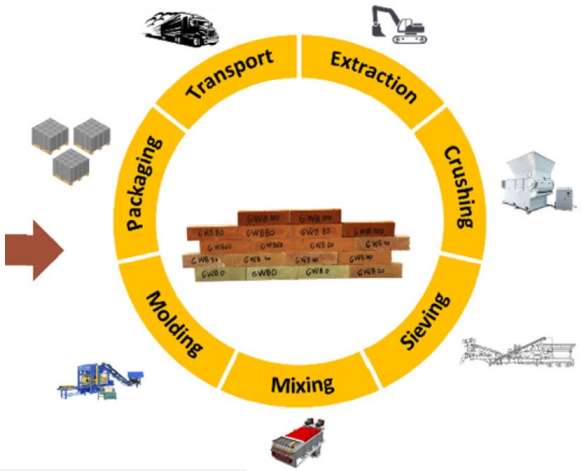
Actual full-scale CBB dimensions (l x w x h): 7-7/8” x 3-9/16” x 2-5/8”

Progress and Current Status of Project TEA

CBB Composition



CBB process



CAPEX

- Procedure
- Storage of raw materials
- Crushing & screening
- Mixing & forming
- Cutting & coating
- Storage of product

OPEX – Feedstocks:

Anthracite coal

Binder material:

- HDPE
- PP
- Nylon 66
- Epoxy 862/3140

PennState College of Earth and Mineral Sciences | John and Willie Leone Family Department of Energy and Mineral Engineering

Progress and Current Status of Project Market Survey

Usage and features of different clay brick types

Common red

- 2nd class brick
- Structural applications
- Used internally or covered with a veneer
- Not weatherproof
- No consistency in size, shape, or color

Face (including thin brick)

- 1st class brick
- Structural applications (except thin brick)
- Used in exposed brick structures or exterior applications
- Weatherproof
- Texture and color are key characteristics
- Thin brick is simply a veneer and may be made of cement, fiberglass, or other material

Engineered (includes fire / refractory bricks)

- Multiple uses
  - Foundations
  - Reinforced walls
  - Civil projects(e.g., sewers and tunnels)
- Fire pits and fireplaces
- Resistant to water and heat damage
- Fire bricks may offer highest heat protection and may be made from ceramic

Glazed (can be clay or concrete)

- Similar to face bricks
- Have ceramic coating
- Used in structural walls, partition walls, or veneers
- Decorative
- Resists graffiti, stains, impacts, and fire
- Long lasting
- Heavier than most clay bricks
- More labor-intensive installation

Progress and Current Status of Project Market Survey

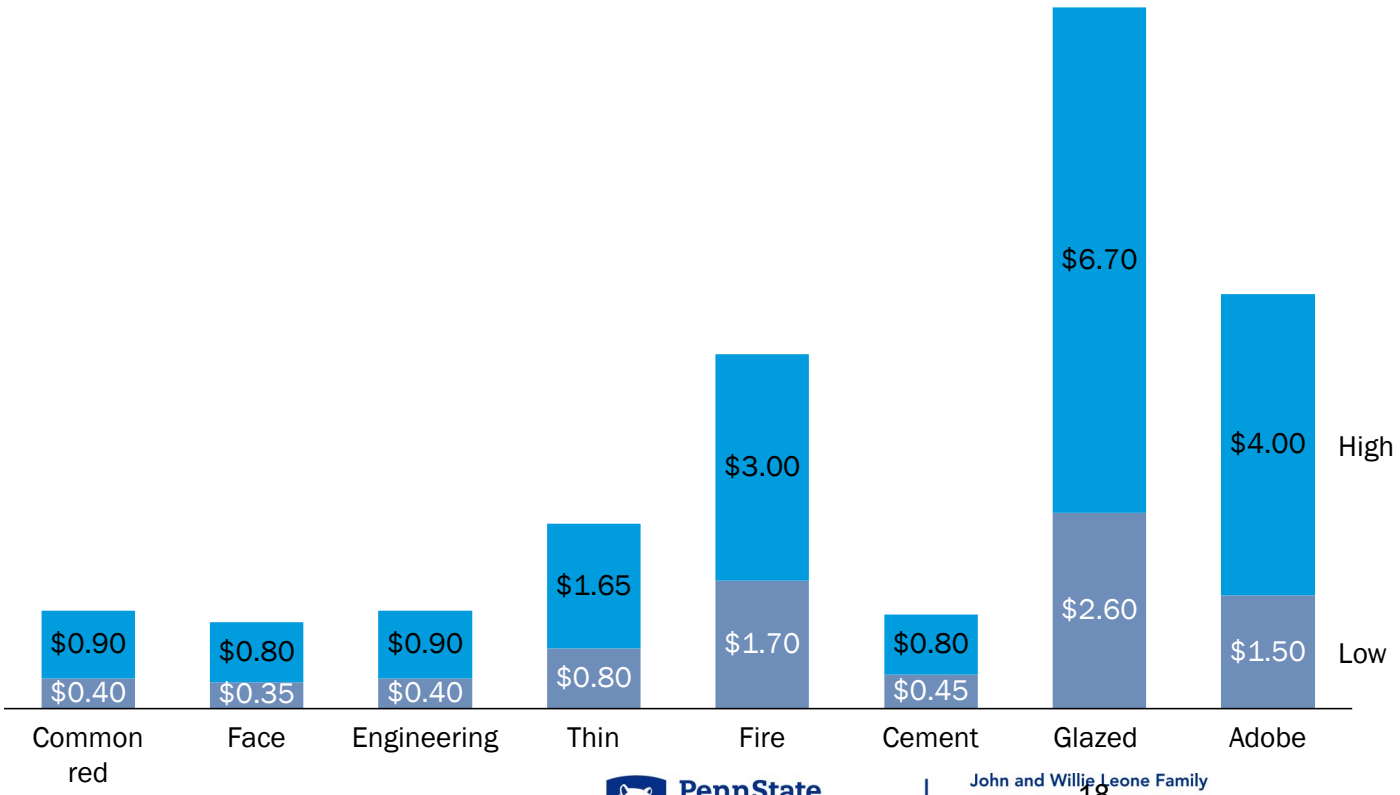
Brick type	Manufacturing process	Benefits	Primary use
Cement / concrete bricks	• Made using cement, sand, coarse aggregates, and water • Can be made on site	• Easily pigmented during production • Superior strength • Block heat, noise, and resist water	• Internal brickwork • Retaining walls • Load-bearing structures (except below grade)
Fly ash bricks	• Made using fly ash and cement (most similar to concrete blocks) • May contain clay, sand, or lime	• Resistant to weather. • Superior frost prevention, fire insulation, and resistance to water.	• Alternative to normal clay bricks. • Used in masonry structures
Sand lime bricks	• Mixing sand, fly ash, and lime • Bonded together by chemical process rather than kiln dried	• Strong and durable • Resists water, wind and heat • Easily pigmented • Requires less mortar during construction	• Structural foundations • Exposed brick and pillars, • Ornamental uses (when pigmented)
Sun-dried bricks (includes adobe)	• Also referred to as unburnt clay bricks. • Made by drying clay bricks to sun exposure.	• Soft • Generally, less expensive bricks	• Temporary structures • Adobe popular in SW USA – requires stucco coating

Source: The Spruce; Waterproof Caulking, The American Ceramic Society

Progress and Current Status of Project Technology Gap Analysis

	Technology gap
1	The extrusion process requires modification to allow adequate cooling and solidification of the CBB mixture.
2	CBBs made from the two viable binder options need to be evaluated to see if they meet the technical standards to compete with other bricks.
3	Glazed and thin bricks sell for premium prices; can the manufacturing process be modified to create these specialty bricks?
4	A more in-depth market/consumer analysis is required to determine if end users are open to CBBs.
5	ASTM Standards testing for intended uses.
6	Field testing

Progress and Current Status of Project Technology Gap Analysis



Source: Homeguide, 2022

PennState College of Earth and Mineral Sciences | John and Willie Leone Family Department of Energy and Mineral Engineering

Plans for future testing/development/commercialization

TEA Findings	
1	The main differences are different feedstocks and the absence of the energy intensive curing process.
Market Survey	
2	Beyond fire clay bricks, there are multiple other brick types that the CBBs would compete with including: concrete bricks, fly ash bricks, and sand lime bricks.
Technology Gap Analysis	
3	The extrusion process requires modification to allow adequate cooling and solidification of the CBB mixture.

PennState
College of Earth
and Mineral Sciences

and

Summary Slide

Key Findings

- Validated hot press molding and extrusion feasibility for fabrication quarter- and half-scale bricks.
- Can achieve 70 wt.% coal loading within thermoplastic and thermoset binders as matrices.
- Compressive strengths comparable to clay-based bricks.
- ~ ½ the weight of clay-based bricks, impermeable and not subject to corrosive environments.
- TEA – CBBs can be price competitive for some applications.
- Market Survey– favorable array of brick types and uses to enable market entry
- Gap Analysis – process optimization, scaling and ASTM tests required prior to market entry.

Lessons Learned

- DoE matrix: particle size, loading and plastic
- Processing temperatures

Take-away

- ***CBBs' compressive strengths are comparable to those of standard clay bricks.***

Technology Summary

Features of coal bricks	Discussion
Equivalent strength	▪ **Strength comparable** to the lower range of traditional clay bricks (although not as brittle)
More impermeable to water	▪ Although clay bricks are moisture resistant, they still are a porous medium ▪ **Reduced porosity and permeability of coal bricks** provides greater moisture resistance and protection against degradation due to freeze-thaw cycles ▪ **Reduced permeability and lack of salts** in feedstocks prevents efflorescence that can ultimately reduce the integrity of bricks
Weigh less	▪ **Coal bricks can be up to 70% lighter** than regular brick ▪ Reduced weight can lower building and transportation costs
More sustainable	▪ **Manufacturing coal bricks does not require natural gas fired kiln drying, greatly reducing energy usage** ▪ Clay mining process is not environmentally friendly and results in deforestation and topsoil erosion

CBB Strength Testing

Appendix I

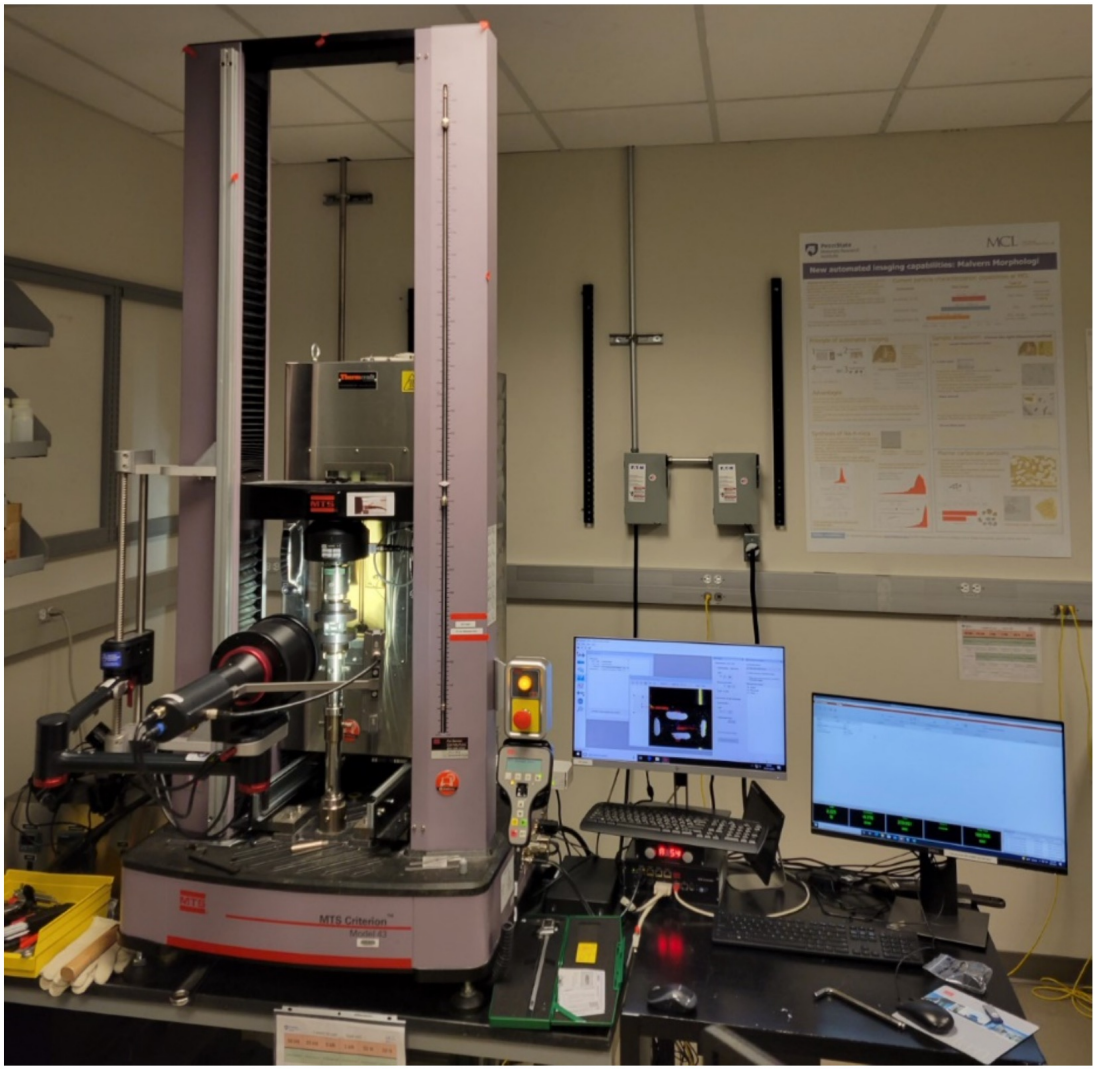


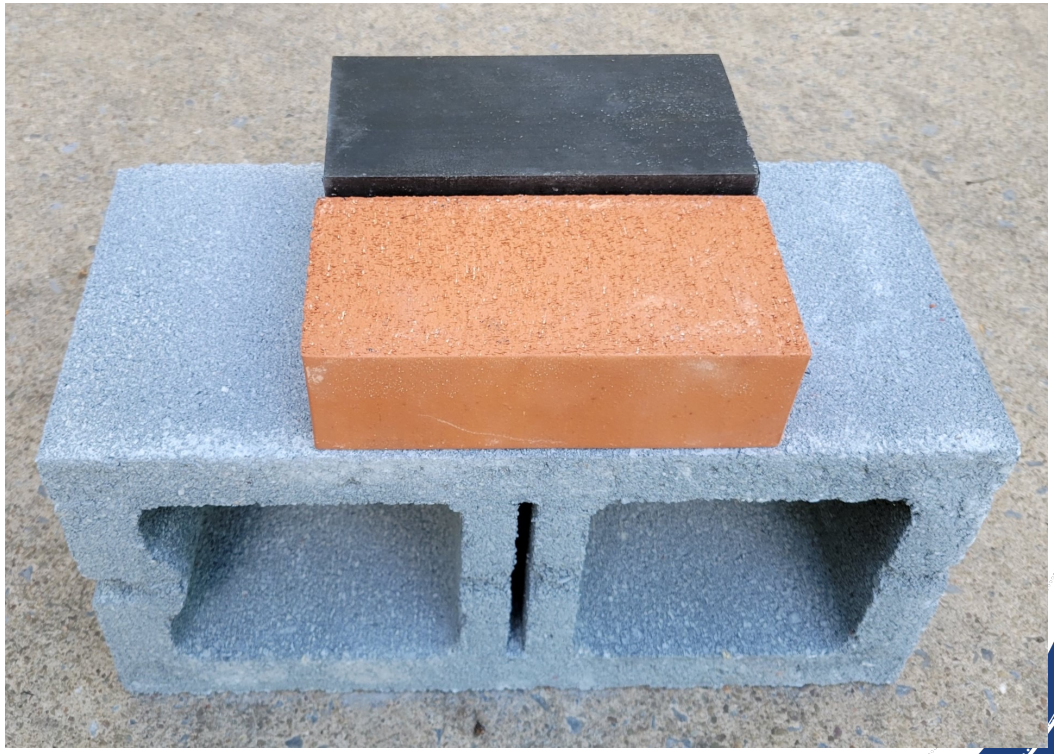
Figure 15: 50 KN MTS Criterion Load Frame

CBB Strength Testing

Procedure:

1. Composites were placed on a flat portion of asphalt containing no loose stones
2. The hit from the sledgehammer was directed to the center of the composite
3. The composite was struck until at least 25% of the total volume had broken off into individual pieces

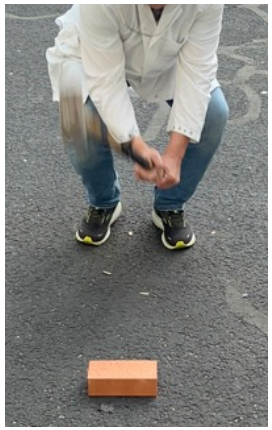
Clay Brick & Cinder Block Size Comparison to a CBB



Clay Brick & Cinder Block Strength Testing

First hit

Second hit



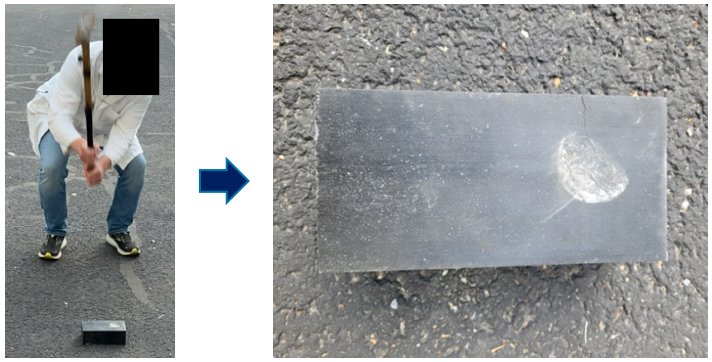
First hit

Notably, since 50% of the cinder block was broken on the first hit, it was considered broken at that point. Thus, both the cinder block and clay brick were broken after the first hit.

PennState College of Earth and Mineral Sciences

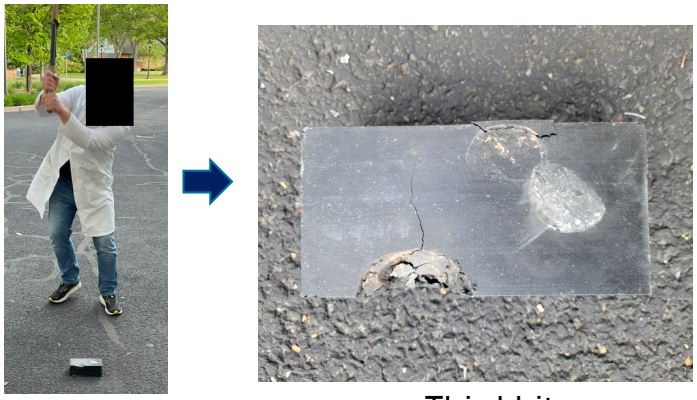
John and Willie Leone Family Department of Energy and Mineral Engineering

CBB Strength Testing on V-PP Composite



First hit

A V-PP test composite was chosen for this strength comparison as its physical properties most closely align with clay and cementitious materials relative to other thermoplastic species. Notably, HDPE would deform, rather than fracturing, which is characteristic of brittle materials.



Third hit

Fifth hit

Timelapse of Fractured V-PP CBB Composite

CBB after the first hit with the sledgehammer shows only a small crack

CBB after the third hit with the sledgehammer remains intact despite exhibiting two cracks through its mid-section

CBB after the fifth hit with the sledgehammer broke into two pieces

Landscape View of All Fractured Composites